SHAPE MEASUREMENT OF SMALL OPTICAL TARGETS

D.J. Baker, Project Director
C.K. Rushforth
M.C. Austin
R.W. Harris

Electro-Dynamics Laboratories
Departments of Electrical Engineering, Physics, and Chemistry
UTAH STATE UNIVERSITY
Logan, Utah

Contract No. AFI9(628)-3825
Project No. 8663

FINAL REPORT

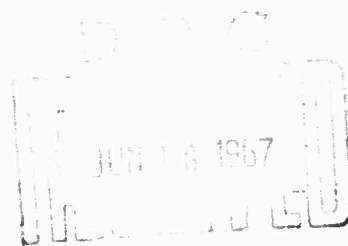Period Covered: 1 Nov 63 to 31 Jan 67

30 April 1967

Dr. George A. Vanasse
Contract Monitor

Distribution of this document is unlimited.

Prepared for
Air Force Cambridge Research Laboratories
Office of Aerospace Research
UNITED STATES AIR FORCE
Bedford, Massachusetts

AFCRL-67-0289

SHAPE MEASUR_MENT OF SMALL OPTICAL TARGETS

D. J. Baker, Project Director
C. K. Rushforth
M. C. Austin
R. W. Harris

Electro-Dynamics Laboratories
Departments of Electrical Engineering, Physics, and Chemistry
UTAH STATE UNIVEF ITY
Logan, Utah

Prepared for

ABSTRACT

Techniques were developed to determine the shapes of optical objects from images corrupted by noise, diffraction and aberrations. Theoretical and experimental investigations were conducted using these techniques. The major part of the study has been reported in detail in several Scientific Reports but is reviewed here, along with the results of some preliminary and subsidiary work.

CONTENTS

LIST OF FIGURES

OBJECTIVES

The overall objectives of this investigation were the derivation of effective optical methods for the determination of the shapes of objects and the evaluation of these methods. Initially, attention was to be confined to a few standard shapes such as circles, rectangles, and triangles. The basic limitations imposed on system design and performance by diffraction and noise were to be investigated both theoretically and experimentally, as well as the effects of such perturbations as non-uniform illumination, aberrations, and film granularity. These objectives were essentially adhered to, with the main emphasis being placed upon theoretical investigations.

INTRODUCTION

This final report summarizes the work accomplished under Air Force Cambridge Research Laboratories Contract No. AF19(628)-3825. This study was done under Project No. 8663 of the Advanced Research Projects Agency and under Project ED-30 of the Utah State University Electro-Dynamics Laboratories. A list of scientific reports and publications resulting from study under this contract are found at the end of this report.

TECHNICAL RESULTS

The first part of this report describes some of the preliminary
studies that were carried out to determine the effects of object illumination
and diffraction on the ability to discriminate between simple objects. The
second part briefly describes the results of the basic work reported o.·
in the interim Scientific Reports that resulted from this contract. For the
detailed results, reference should be made to the Scientific Reports.

Preliminary Study

Diffraction and Fourier analysis

It has been shown that if attention is limited to Fraunhofer diffraction,
the techniques of Fourier analysis can be used to investigate the perfor-
mance of an optical system. The system can then be treated as a linear
filter of spatial frequencies whose properties are described by a transfer
function analogous to that of an electrical filter. For incoherent illumin-
ation, the spatial-frequency spectrum of the image is found by multiplying
the spatial-frequency spectrum of the object by the system transfer function.

Alternately, the image intensity distribution may be viewed as the
convolution of the object intensity distribution with the point spread
function of the optical system. The point spread function is simply the

image intensity distribution due to a point source and is analogous to the impulse response of an electrical filter. It is the Fourier transform of the system transfer function.

By viewing the image intensity distribution as a convolution, one can quickly obtain a qualitative understanding of the effects of diffraction. For a circular aperture, the point spread function is the well-known Airy pattern of the form

$$\left[2 \, \frac{J_1(\alpha r)}{\alpha r} \right]^2$$

This pattern has a central maximum whose width is inversely proportional to the aperture radius, together with fringes or sidelobes which decrease rapidly in strength as r increases. Convolution with this pattern produces an image which is a smeared version of the object. The amount of smearing increases, of course, as the width of the Airy pattern increases. Hence, if the object (represented in the appropriate coordinate system) is very large compared with the Airy disc, the smearing produced by diffraction will be negligible.

As the size of the object relative to the size of the Airy disc is reduced, smearing becomes more important. For example, the corners of a square become more and more rounded, and it becomes increasingly more difficult to discriminate between a square and a circle. As the object sizes continue to be reduced, a condition will be reached at which

discrimination is not sufficiently reliable. This limit will depend on the patterns to be classified, the method of classification or recognition, the characteristics of the noise in the system, and the degree of reliability required.

Theoretical imaging and discrimination

As was pointed out earlier, the spatial-frequency spectrum of the output (image) can be written as the product of the spatial-frequency spectrum of the input (object) and an appropriately defined system transfer function. Alternately, the image intensity distribution may be viewed as the convolution of the object intensity distribution with the point spread function of the system. These two characterizations provide two alternate methods of studying the effects of the optical system upon the object. For some purposes, it is more convenient to work in the spatial-frequency domain, while in other cases the intensity-distribution domain is more convenient.

These techniques can be applied to the problem of determining the effects due to diffraction by a finite circular aperture. In order to isolate the effects of diffraction from other sources of perturbation, the problem should be formulated in as simple a form as possible. Specifically, the problem considered could be the following. Assume that one of a finite number of exactly known objects (e.g., triangle, square, circle) is present at the input to an optical system. In addition to the object, a

certain amount of background radiation is present. The intensity distribution in the image plane is thus a perturbed and filtered version of the original object. It is desired to observe this image-plane intensity distribution and to determine which object is present at the system input.

An efficient decision scheme can be devised by using the techniques of statistical decision theory. The problem can be considered as that of deciding which member of a set of known (or partially known) signals has been received. Using the techniques of statistical decision theory, the optimum or near-optimum extraction or classification procedures can be derived for various noise environments. In addition, if the model is sufficiently simple, the performance of these procedures can be evaluated according to a criterion such as the probability of misclassification. Within this framework, the effects of diffraction, aberrations, nonuniform illumination, film granularity, and perhaps other phenomena on the performances of various classification procedures can be investigated.

Under certain reasonable assumptions, it can be shown that the optimum decision scheme uses correlation techniques on matched filters. Even when they are not optimum, such techniques have been shown to give good results. It is important to note that direct application of these techniques requires that the patterns to be classified are known exactly. When this assumption is relaxed, the decision procedure must be modified accordingly.

One problem which has not beer mentioned thus far is that of filter mismatch (i. e., matching a filter to the wrong signal). This problem will be important for two reasons. Fi st, if we match the filter to the object itself (e. g., a circle), it will not be matched to the image, since the image has been affected by the finite aperture. In principle, we should match to the intensity distribution which results when the object intensity distribution is convolved with the system point spread function. To do this exactly, however, is often impractical; hence, our filter will usually be at best slightl mismatched.

A second potential cause of filter mismatch is nonuniform illumination of the object. If the distribution of intensity across the object is exactly known to us, we can again, in principle, achieve a filter which is exactly matched. In practice, there will usually be some mismatch due to our lack of precise knowledge concerning the object illumination.

The foregoing discussion indicates the necessity for considering the effects of filter mismatch in evaluating the performance of a matched-filter classification system. These effects are included in Scientific Report No. 4.

It should be emphasized again that the work described above presupposes precise knowledge of the shape, size, and position of all the patterns to be classified. This is certainly a reasonable starting point, because it tends to remove any extraneous sources of uncertainty, thereby

allowing us to concentrate on the effects of diffraction. In most practical situations, however, such precise knowledge regarding the patterns will not be available. Hence, it will be necessary to modify the decision procedures accordingly. An additional complicating factor is the fact that we will often be interested in automatic pattern classification by machine. Hence, we seek techniques which utilize the incomplete information available in a way which can be easily automated. In many cases, the only information available about the patterns to be classified will be samples of these patterns. This fact leads to a consideration of machine learning or adaptation.

Preliminary experimental imaging and discrimination

Sources with uniform and non-uniform illumination were constructed to experimentally determine the effects of such illumination on the ability to classify patterns. The results for various geometrical and illumination parameters are reported here.

Uniform illumination

A uniformly-illuminated set of patterns (triangles, squares, and circles) on a black background was photographed with the lens 25 feet from the patterns. The size of each of the patterns is given in Table 1.

Table 1. Image pattern size.

Pattern No.	Square Side (in.)	Triangle Altitude (in.)	Circle Diameter (in.)	Angle Subtended (Rad.)
1	0.0625	0.0625	0.0625	2.08×10^{-4}
2	0.125	0.125	0.125	4.16×10^{-4}
3	0.250	0.250	0.250	8.3×10^{-4}
4	0.500	0.500	0.500	16.7×10^{-4}

The angle subtended by the pattern is found by dividing the distance across the patterns by the distance from the pattern to the lens. The size of the Airy disc is given by
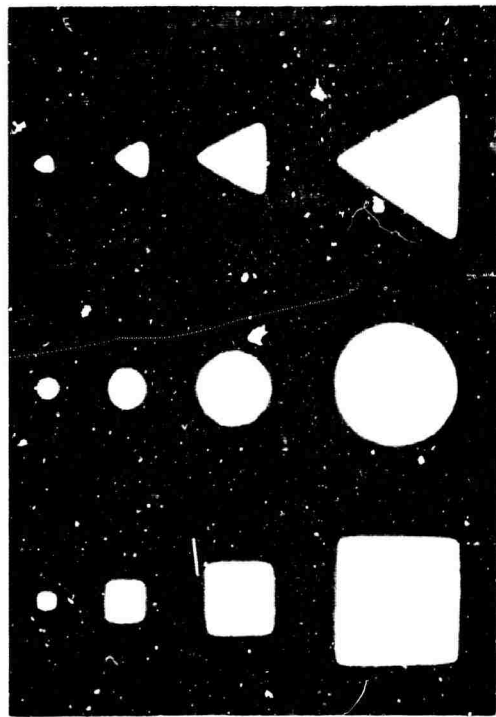
$$\theta = 1.22 \, \lambda/d$$

where λ is the wavelength of light and d is the diameter of the lens aperture. The circular apertures and the corresponding Airy disc size are listed in Table 2.

Table 2. Airy disc for various circular apertures.

Aperture No.	Size of Aperture Diameter (in.)	Airy Disc (radians)
1	0.640	3.77×10^{-5}
2	0.484	4.97×10^{-5}
3	0.323	7.44×10^{-5}
4	0.242	9.94×10^{-5}
5	0.173	1.39×10^{-4}
6	0.120	2.01×10^{-4}
7	0.081	3.00×10^{-4}
8	0.060	4.02×10^{-4}
9	0.040	6.02×10^{-4}
10	0.028	8.59×10^{-4}
11	0.020	1.20×10^{-3}
12	0.014	1.78×10^{-3}

Figure 1 shows a portion of the results of photographing each pattern after having been diffracted by the circular apertures listed in Table 2. The photograph taken with aperture No. 6 (Airy disc 2.01×10^{-4} radians, pattern angle subtended 2.08×10^{-4} radians) is the first photograph in which the smallest patterns are visually indistinguishable. For aperture No. 8, the second row of patterns (Airy disc 4.02×10^{-4}, pattern angle

11
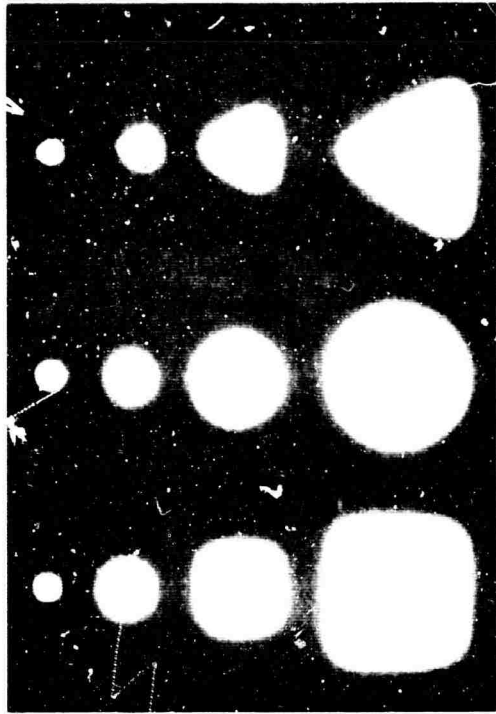
Aperture No. 5

Aperture No. 8

Aperture No. 1

Aperture No. 6

Figure 1. Photographs showing diffraction limiting of small objects.

subtended 4.16×10^{-4} radians) approaches the limit at which the
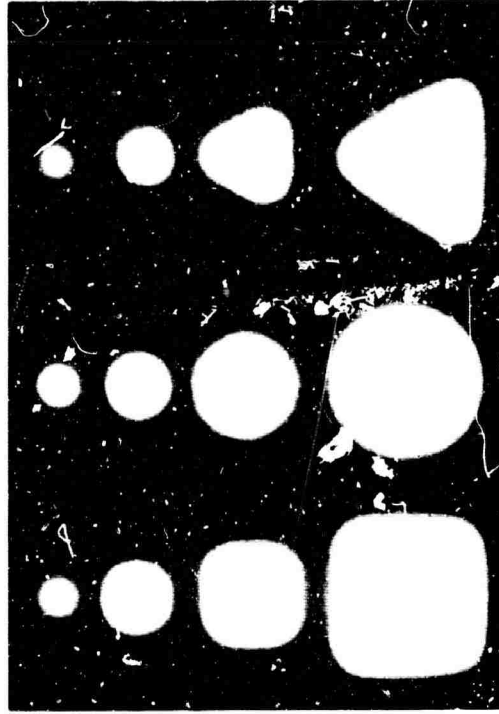
geometrical shapes can be visually distinguished. The crucial relationship

shown by these photographs is this: When the ratio of the Airy disc size

to pattern angle subtended is unity (or greater), then visual recognition of

the various patterns is not reliable. This relationship is discussed further

in Scientific Report Nos. 8 and 9.

Visual diffraction limiting of a uniformly illuminated rocket pattern

is shown in the photographs of Figure 2. Notice that the tail structure

(shape of the fins) is visually obscured when the ratio of the Airy disc and

the smaller dimensions of the rocket (7.29×10^{-4} radians) approaches

unity. In the last photograph (aperture No. 12) even the gross longitudinal

features of the rocket are obscured.

Nonuniform illumination

The visual obscuration effects of diffraction can be even more severe

when the objects to be distinguished are nonuniformly illuminated. To

obtain a qualitative visual estimate of the effects of nonuniform illumination,

two nonuniformly illuminated square sources were diffracted by various

sizes of circular apertures.

The optical system used is shown in Figure 3. The lenses L_1 and L_2

serve to reduce the distance between the object plane and image plane over

the system previously used for the uniformly illuminated sources. The
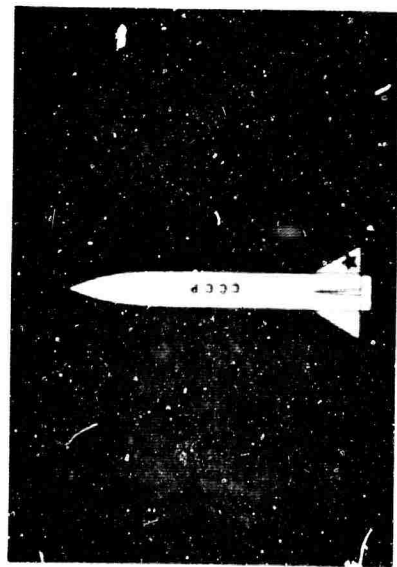
Aperture No. 1
(airy disk size 3.77×10^{-5} radians)
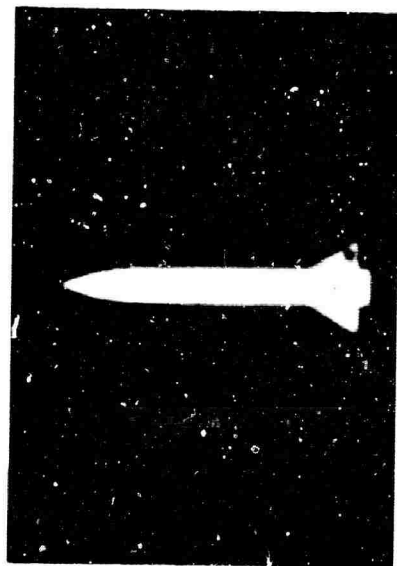
Aperture No. 4
(airy disk size 9.94×10^{-5} radians)
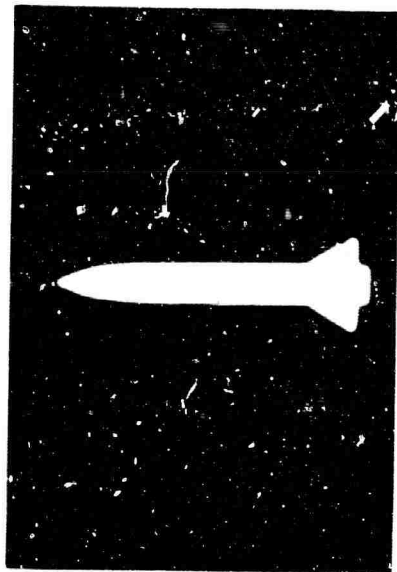
Aperture No. 6
(airy disk size 2.01×10^{-4} radians)
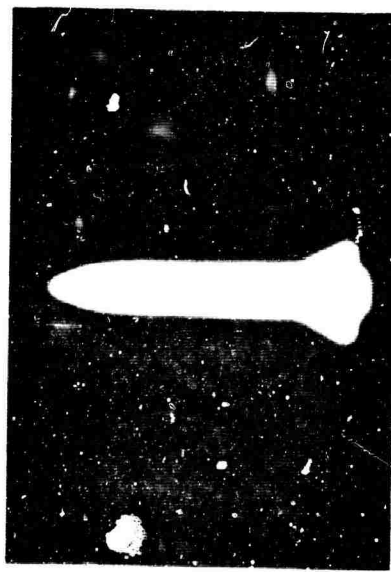
Aperture No. 8
(airy disk size 4.02×10^{-4} radians)
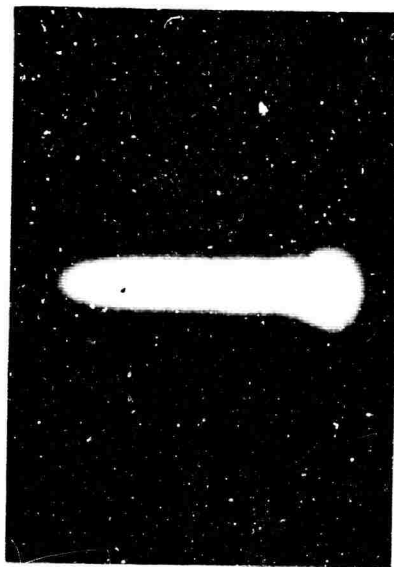
Aperture No. 10
(airy disk size 8.59×10^{-4} radians)

Aperture No. 12
(airy disk size 1.78×10^{-3} radians)

Figure 2. Photographs showing diffraction limiting of a rocket pattern (angle subtended by rocket pattern: 6.04×10^{-3} by 7.29×10^{-4} radians).

13

14

Object Plane $\quad$ Lens L_1 $\quad$ Aperture Plane $\quad$ Lens L_2 $\quad$ Image Plane

Circular Aperture
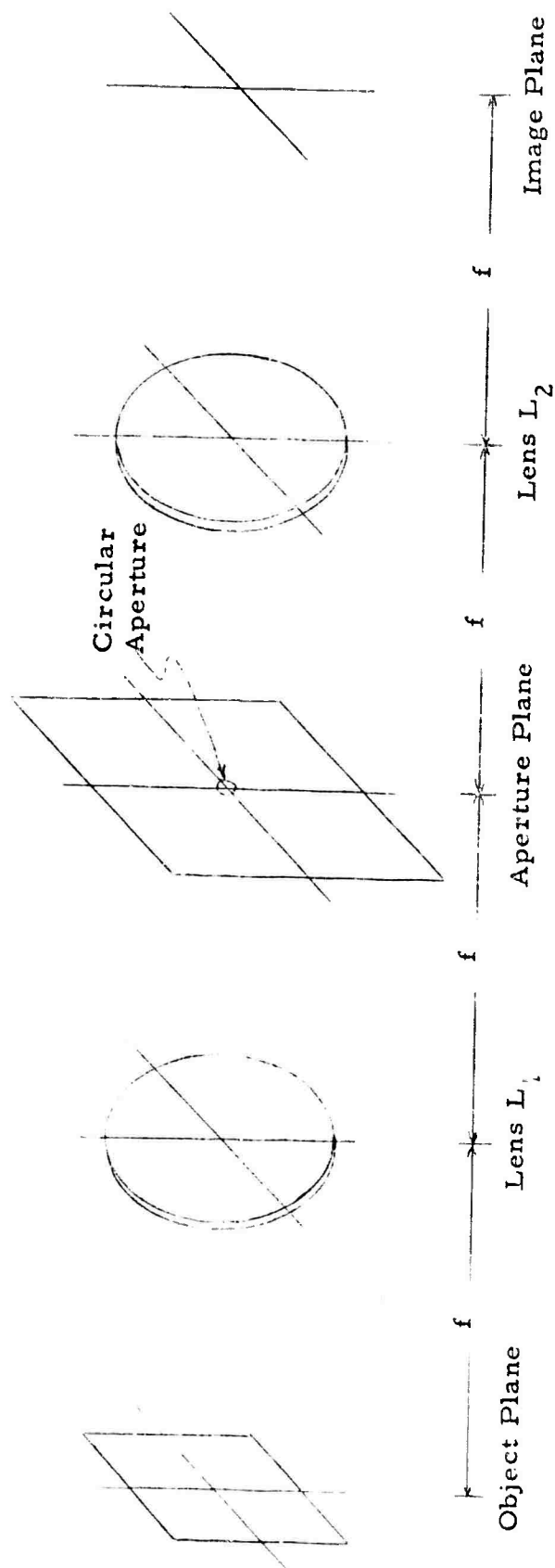
Figure 3. Optical system used to illustrate the diffraction effects on nonuniformly illuminated square sources.

Fourier techniques referred to previously are valid for both systems.
The two sources were made from negatives of nonuniformly exposed
photographic film and then illuminated trom behind to produce the desired
nonuniform sources. Figure 4 shows microdensitometer tracings of the
sources used. The nonuniformity is clearly evident and shows a linear
variation of approximately 100:1 in contrast.

Figure 5 presents a few of the photographs obtained with this system.
The top two photographs 5(a) and 5(b) are the sources imaged through the
optical system when no appreciable diffraction is present (No. 7 aperture).
Figures 5(c) and 5(d) show the results when more diffraction is present
(aperture No. 9). The exposure times for photographs 5(c) and 5(d) were
identical. Increasing the diffraction still further (aperture No. 10)
produced the photographs 5(e) and 5(f). The exposure times for 5(e) and
5(f) were identical.

A visual comparison of 5(c) with 5(d) and 5(e) with 5(f) shows that the
diffraction effects are definitely more severe when the corners of the
square are less brightly illuminated. A very rough (but informative)
quantitative statement of the effects of nonuniform illumination can be
made as follows. Suppose we decide visually that the diffraction imposed
by aperture No. 9 is sufficient to obscure the object shape for the photo-
graph in 5(c), but the object shape for the series 5(b), 5(d) and 5(f) is not
obscured until aperture No. 10 is used in 5(f). Such a visual decision
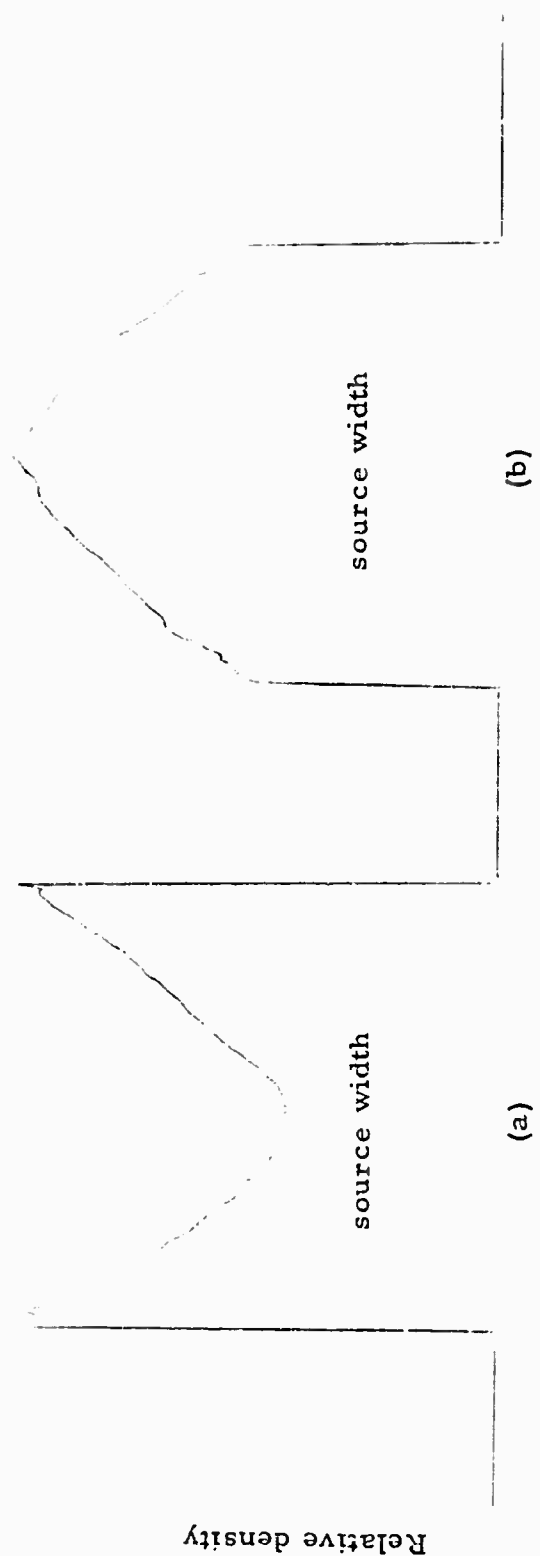
Figure 4. Microdensitometer tracings showing the nonuniformity in illumination for the two sources used. Tracings (a) and (b) correspond, respectively, to the sources that produced the undiffracted images of Figures 5(a) and 5(b). (The relative density of the tracings is inversely related to light illumination.)

16

(a)

(b)

(c)

(d)

(e)

(f)
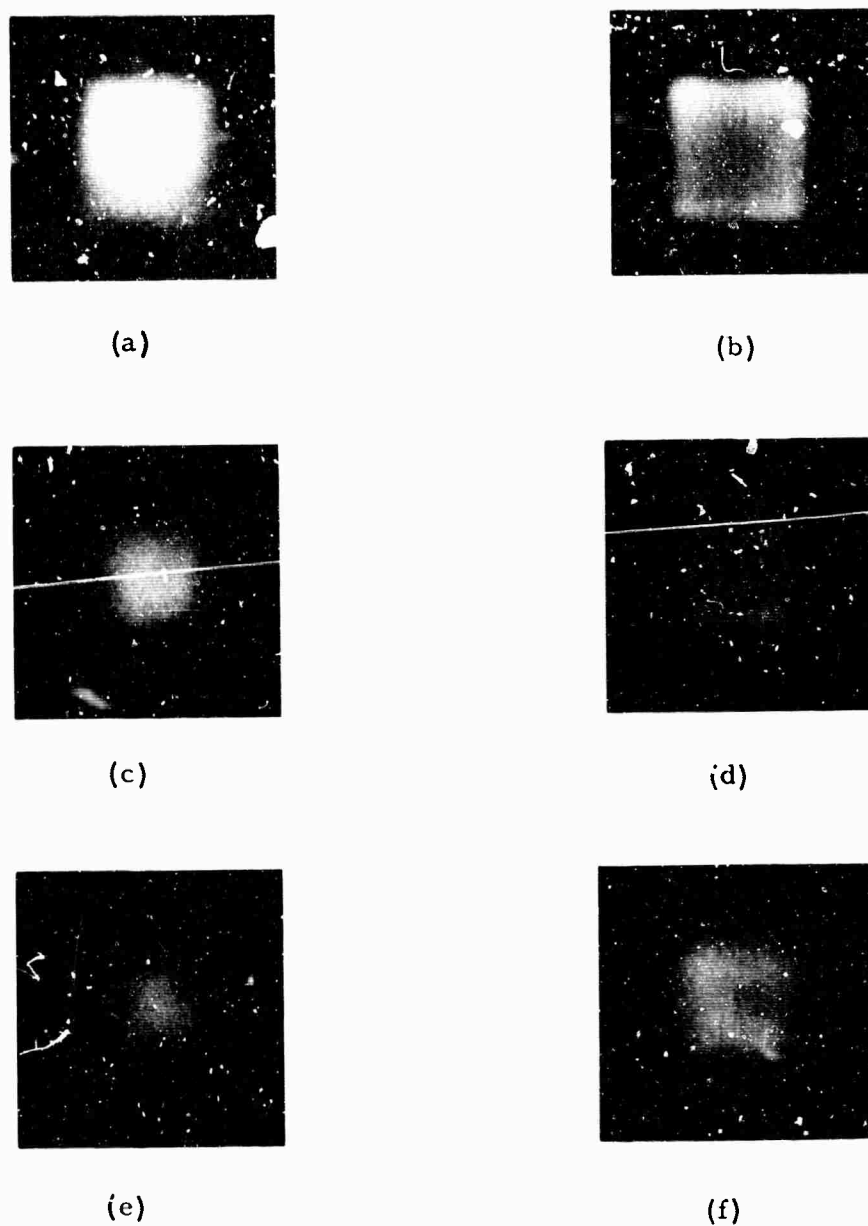
Figure 5.   Photographs (a) and (b) show two nonuniformly ... minated
             objects imaged through the optical system when no appreciable
             diffraction is present.   Photographs (c) and (e) are diffracted
             (aperture Nos. ? and 10, respectively) versions of (a).
             Photographs (d) and (f) are diffracted (aperture Nos. 9 and
             10, respectively) versions of (b).

allows one to state that the nonuniformly illuminated source with bright

corners can withstand 40% more diffraction than the source with dim

corner . This statement, of course, depends upon the dynamic range

(relative contrast in intensity) and distribution of the nonuniformity of the

source illu. ination. Further quantitative statements in mathematical

terms are presented in Scientific Report No. 4.

To summarize, it is noted that: (1) When the objects are uniformly

illuminated, diffraction sufficient to visually obscure object shape occurs

when the ratio of the Airy disc to the object size is unity or greater;

(2) When details of the object are less brightly (nonuniformly) illuminated,

e visual diffraction limit occurs when the above ratio is less than unity.

To visually discriminate between various objects beyond these limits will

in general require restoration procedures (Scientific Report No. 8) to be

performed.

SUMMARY OF SCIENTIFIC REPORTS
GENERATED UNDER THIS CONTRACT

An important problem in optical data processing is that of determining whether or not a particular pattern or signal is present in the image plane of an optical system. Various versions of this problem can be obtained, depending on the prior knowledge available about the pattern or signal to be detected and the noise in the system. The methods of statistical decision theory can be used to derive optimum detection procedures which depend on this prior information and on the costs of the different types of errors.

The problem of recognizing patterns in photographs was considered [1]. There are many important problems which require recognition or classification of optical patterns in the presence of background radiation. In many such problems, the data to be analyzed consist of one or more photographs of the noisy pattern which is to be classified. The accuracy of any procedure for classifying patterns in photographs will, in general, be limited by such factors as atmospheric distortion, lens diffraction and aberration, and film granularity, as well as by the ambient background radiation.

For the specific case considered, the patterns to be classified were assumed to be exactly known immediately prior to their impinging upon the film. Making this assumption amounts to ignoring atmospheric distortion

and assuming that, if diffraction and aberration are important, their effects on the pattern are known. The photographs were assumed to be sampled and quantized to form a binary vector (i. e., the elements of the vector consist of ones and zeros depending, respectively, upon whether the quantized pattern elements are present or absent). It was found that the optimum classification procedure performs nonlinear operations on the received signal vectors. For uniform pattern illumination or low signal-to-noise ratio, the optimum procedure reduced to one using matched-filter techniques. The analysis applies not only to the specific problem mentioned here but can be applied to any situation in which the patterns to be classified can be represented by binary vectors.

Another problem considered, which is similar to the one above, was the problem of detecting an optical pattern whose shape and orientation are known but whose position is unknown [2]. Two detection procedures were investigated for this case--one which entailed a search procedure and one which did not. The false-alarm and false-dismissal probabilities (i.e., respectively, the probability of saying the "signal" is present when it is absent and the probability of saying the "signal" is absent when it is present) for these two procedures were evaluated under certain simplifying assumptions in order to compare the two procedures with each other and with the detector which is optimum when the position of the pattern is known. It was shown that there is a trade-off between error rate and

information rate. The procedure requiring a search technique processes the data less rapidly but at the same time achieves a lower error rate for a given signal-to-noise ratio. The choice of procedure will depend on the signal and noise parameters and on the performance required. This analysis can also be applied to the problem of detecting a signal with unknown arrival time.

The effects of diffraction and additive noise on the ability to discriminate between two known optical intensity distributions were investigated [4]. Specifically, the problem of discriminating between an incoherently illuminated circular source and an incoherently illuminated rectangular source, both of which had been diffracted by a circular aperture, was considered. While this problem may be somewhat artificial, it nevertheless provides considerable insight into the ultimate limitations on system performance due to diffraction and noise.

In order to obtain quantitative results pertaining to the design and evaluation of a discrimination procedure, it was necessary to specify a particular noise model. The model used was based on the assumption that the intensity distribution in the image plane impinges on a photosensitive detector whose output consists of photoelectrons which obey a Poisson distribution. The model was discussed in some detail, and the associated optimum discrimination procedure was obtained. Because this optimum procedure would be hard to implement, some important sub-optimum procedures were also considered. It was shown that a key quantity in

assessing the effect of diffraction on our ability to discriminate between two different objects is the integrated square of the difference between the images produced by the two objects. This quantity is an important performance criterion in its own right, and the results pertaining to it are not tied to the particular noise model mentioned above. The results of the evaluation of the discrimination procedures were in the form of integrals which were not easily evaluated by analytical means. These integrals were evaluated numerically, and the results were presented and discussed. Typically, it was shown that the ability to discriminate drops off quite rapidly as the size of the Airy disc approaches the size of the object.

The detectors devised for the above studies were fixed-sample detectors, that is, detectors for which the number of samples or sample duration is fixed in advance. Another fixed-sample detection problem was studied for which the objective was to discriminate between optical signals which had been distorted by diffraction, additive background noise, and multiplicative noise [8]. For this study Poisson statistics were assumed, and the observed output vectors consisted of the number of photoelectrons. The structure and performance of fixed-sample detectors designed for random or unknown objects (optical signals) as well as known objects were investigated. Optimum procedures, in the sense of minimum risk, were derived for detecting known and unknown objects.

The study of the performance of these detection procedures illustrated the effect of uncertainty about the object.

A basic and important problem in optical data processing is to determine in as short a time as possible the presence or absence of an object in the field of view of a.i optical instrument. When time is important, as it is in many situat'ons, one is led to consider sequential data processing procedures instead of conventional fixed-sample proced ur s. In a sequential detection procedure, the number of samples is determined by the course of the experiment. If the received data are relatively noise-free, a reliable decision may be made quickly, while for very noisy data the test may last considerably longer. The sequential detection test has a shorter average test length than the fixed-sample test of the same accuracy.

A study was made of the problem of sequentially detecting a signal whose amplitude was fixed but initially unknown to the system designer [6]. Under the assumption that the signal was drawn from a Gaussian population with known parameters, the sequential likelihood-ratio detecto- for detecting the signal in the presence of Gaussian noise was derived. The amount of information per sample provided by this detector was calculated and compared with that for a detector designed for a specific signal strength. This quantity provides considerable insight into the adaptive capability and the performance of the detector. The average sample number (ASN) necessary to make a decision with a prescribed

error probability was investigated using approximate analytical techniques in conjunction with computer simulation. This detector was compared with a sequential detector designed for a specific signal strength and was shown to achieve considerably greater protection against making decision errors for the presence of small signals at the cost of an increased average test length. An approximate analysis was shown to be in good agreement with results obtained by computer simulation.

Sequential detection was also considered for the more realistic case in which the noise and signals obey Poisson statistics [8]. Sequential detectors were derived for various cases of known and unknown optical signals and their performances were compared. The information per sample and ASN were determined and compared for these various cases. For most of the cases considered, analytical solutions were extremely difficult to obtain; hence, the analysis was, to a large extent, carried out by computer simulation.

In the detection or discrimination studies discussed above, we were concerned with the problem of determining which of a finite number of states of nature (usually two) was the correct one. The problem of estimation is closely related to that of detection. The difference between the two problems is that in the estimation problem the possible states of nature form a continuum, whereas in the detection problem they form a discrete set. Thus, the estimation problem may be thought of as a

detection problem with a continuum of possible states. A large part of

the study effort dealt with the problem of estimating incoherent optical

signals.

The problem of estimating the intensity distribution of an optical

signal which had been distorted by diffraction and background noise was

studied. Under the assumption that the signal and noise were additive,

the optimum linear estimate of the intensity distribution, using the

criterion of minimum mean-square error, was obtained [3]. This

estimate was shown to be a linearly-filtered combination of the a priori

mean and the observed image distribution, with the details of the filtering

depending on the prior information, the noise statistics, and the optical

imaging system. The performance of the optimum estimation procedure

was evaluated for the important special case of large a priori uncertainty.

The optimum procedure for processing multiple observations was also

considered. It was shown that as the number of observations became

large, the estimate approached the true object.

A further study was made of the estimation problem for the presence

of multiplicative noise (detection noise) as well as additive background

noise and diffraction [8]. Poisson statistics were assumed in this study,

since in many real situations Poisson statistics are more realistic than

the more commonly used Gaussian statistics. The performance of the

minimum mean-square-error estimation procedure was evaluated for

several special cases. Some results pertinent to optimum sampling

schemes were obtained for both white and colored additive noise. Other types of estimates were also briefly considered.

A basically numerical approach was applied to the problem of estimating or restoring optical signals which are obscured by diffraction and noise [7]. The numerical approach used was to operate directly on the noisy image and point spread function (impulse response of the optical system) rather than on the Fourier transform of these quantities. Special emphasis was placed on studying the effect of noise and the use of a priori info ation in the restoration process. Several types of "optimum" estimates of the object intensity distribution were considered. These statistical estimates were compared mathematically, and in many cases numerically, to other non-statistical estimates formulated from control theory and dynamic programming. Extensive numerical results were obtained for the restoration of various one-dimensional objects in the presence of noise. Two monochromatic "point sources" in the presence of noise were shown to be resolved when separated by 1/5 of the Rayleigh criterion distance. Numerical results were also shown for the mean-square error as a function of a priori information, the measuring scheme chosen, and diffraction. Using these result, and having been given an estimate of the noise variance and diffraction, one can to some extent ascertain the detail and resolution expected in the restoration process.

A somewhat different study from those mentioned above was an experimental investigation to develop a procedure whereby the Michelson stellar interferometer could be used to spatially analyze an unknown quasi-monochromatic source [5]. It was found from this investigation that a uniformly illuminated symmetrical source, located far enough from the analyzing interferometer to satisfy Fraunhofer conditions, can be analyzed spatially to determine the absolute size of the source (e.g., source width for the case of a one-dimensional slit source). A continuously variable double slit arrangement was developed and used to uniformly increase the slit separation which was necessary to Fourier analyze the source. The envelope of the intensity curve obtained by placing a fixed detector in the region of the first order of diffraction while the slits were uniformly separated was found to be the visibility curve. The Fourier transform of this curve has been shown to be the intensity distribution of the source.

A study was also made of a real-time Fourier transform technique [7]. It has been found that the spectral distribution of radiation can be obtained by calculating the Fourier transform of the interferogram obtained from a two-beam interferometer. The use of a digital computer has the disadvantage that the spectrum is not available for immediate analysis. The study of a real-time Fourier transform was undertaken to determine the feasibility of computing spectra in real time and building a computer to perform this task.

Varicus computational techniques for performing the required trans-
formation were studied and a real-time Fourier transform synthesizer
was devised. It was designed to be compatible with a lamellar grating
interferometer, but it could be used just as well with a well-compensated
Michelson interferometer. A novel approach was used to obtain the cosine
functions required in the synthesis of the cosine transform. All of the
computations except the summation were performed in analog form, while
the summation was performed digitally. The result of the computation,
the spectral distribution, is available as soon as the interferogram is
obtained. Errors in the technique were investigated and methods of
compensating for them determined. Data were obtained for several test
functions, and the synthesized spectra were compared with the theoretical
values. The results of the spectral synthesis were obtained for several
actual interferograms.

Scientific Reports Generated under Contract No. AF19(628)-3825

1. Rushforth, C.K., Recognizing Patterns in Photographs. Scientific Report No. 1, AFCRL-64-640, Contract No. AF19(628)-3825, Electro-Dynamics Laboratories, Utah State University, Logan, Utah, 1 May 1964.

2. Rushforth, C.K., Detection of a Pattern in Unknown Position. Scientific Report No. 2, AFCRL-64-1011, Contract No. AF19(628)-3825, Electro-Dynamics Laboratories, Utah State University, Logan, Utah, 1 November 1964.

3. Rushforth, C.K., Restoration of Optical Patterns. Scientific Report No. 3, AFCRL-65-181, Contract No. AF19(628)-3825, Electro-Dynamics Laboratories, Utah State University Logan, Utah, 1 March 1965. (Also presented at Opt. Soc. Am. Spring Meeting, 30 March 1965.)

4. Rushforth, C.K., and R.W. Harris, The Effects of Diffraction on Optical Discrimination. Scientific Report No. 4, AFCRL-66-105, Contract No. AF19(628)-3825, Electro-Dynamics Laboratories, Utah State University, Logan, Utah, 1 January 1966.

5. Allen, Royce H., A Continuously Variable Double Slit System and the Fourier Analysis of Michelson's Stellar Interferometer. Scientific Report No. 5, AFCRL-66-399, Contract No. AF19(628)-3825, Electro-Dynamics Laboratories, Utah State University, Logan, Utah, 1 May 1966.

6. Rushforth, C.K., Adaptive Sequential Detection of an Unknown Signal. Scientific Report No. 6, AFCRL-66-491, Contract AF19(628)-3825, Electro-Dynamics Laboratories, Utah State University, Logan, Utah, 1 June 1966.

7. Hoffman, Joseph E., Jr., A Real Time Fourier Transform Synthesizer. Scientific Report No. 7, AFCRL-67-0049, Contract No. AF19(628)-3825, Electro-Dynamics Laboratories, Utah State University, Logan, Utah, 1 November 1966.

8. Harris, R. W., and C. K. Rushforth, Numerical Restoration of Optical Objects Obscured by Diffraction and Noise. Scientific Report No. 8, AFCRL-67-0070, Contract No. AF19(628)-3825, Electro-Dynamics Laboratories, Utah State University, Logan, Utah, 1 December 1966.

9. Austin, M. C., and C. K. Rushforth, Estimation and Detection of Optical Signals Distorted by Diffraction, Background Noise, and Detection Noise. Scientific Report No. 9, AFCRL-67-0071, Contract No. AF19(628)-3825, Electro-Dynamics Laboratories, Utah State University, Logan, Utah, 1 December 1966.

Publications in Professional Journals Generated to Date
under Contract No. AF19(628)-3825

Hoffman, Joseph E., and George A. Vanasse, 1966. Real-Time
Spectral Synthesis in Fourier Spectroscopy, Applied Optics 5:
1167-1169.

Rushforth, Craig K. 1965. Recognizing Patterns in Photographs,
Applied Optics 4:379-381.

Wood, John K., and Royce H. Allen. 1966. A Double Slit with
Continuously Variable Separation, Applied Optics 5:351.

RECOMMENDATIONS FOR FUTURE STUDY

It has been shown (Scientific Report No. 8) that the restoration

of diffracted optical objects is feasible for SNR's which are possible to

achieve in practice. Although the procedure was specifically developed

for and applied to the optics problem, resolution enhancement is obviously

applicable to other areas, such as spectroscopy and radar. In interfer-

ometry, the basic resolution limitation in the power spectrum is due to a

finite path length difference obtainable in the interferometer. Provided

the SNR is high enough, the restoration procedure can effectively extend

the path length difference (mathematically) and thus overcome the physical

limitations in the interferometer. In a particular example, the resolution

has been shown to be doubled when the SNR is as low as 30. We feel that

these results clearly imply that further investigation of the application of

resolution enhancement is both necessary and warranted.

The results of this study (Scientific Report No. 4, Scientific Report

No. 8) indicate that it is more difficult and costly (in terms of SNR) to

restore the entire optical object in every detail than to restore a smaller

set of parameters. For example, for a specific application in the

interferometry case, perhaps only parameters such as the number of

spectral lines in a given region, the spacing between the lines, the line

widths, or the relative magnitude of the lines with respect to a common

reference may be necessary. It appears that these parameters could be

estimated less expensively in terms of SNR than obtaining the entire

spectra. In view of these results, it is recommended that a study be made

which will put on an absolute scale the trade-off between SNR and the error

involved in estimating smaller sets of parameters such as the set mentioned

in the example above.

It is also recommended that the concept of a discrete sequential

detector, described in Scientific Report No. 9, be extended to that for a

continuous sequential detector where only one observation is made but

the duration of the observation is the variable. Also, multiple detection

(fixed-sample and sequential) should be considered for cases with more

than two states of nature. That is, a discrimination procedure might

consist of observing the output vector of the detector and deciding which of

M possible optical patterns is present. The results of this additional stu 'y

as well as the results of Scientific Reports No. 5 and No. 9, could be used

in interferometric spectroscopy for the discrimination of spectra.

ACKNOWLEDGEMENTS

Jay D. Schiffman, Administrative Assistant

Jackie E. Stevens, Photo Technician

Elwood V. Streeter, Research Technician

Arnold A. Thayer, Research Journalist

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
Electro-Dynamics Laboratories	Unclassified
Utah State University, Logan, Utah 84321	2b. GROUP

3. REPORT TITLE

SHAPE MEASUREMENT OF SMALL OPTICAL TARGETS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Scientific Report, 1 November 1963 to 31 January 1967

5. AUTHOR(S) *(Last name, first name, initial)*

Baker, D.J., Rushforth, C.K., Austin, M.C., and Harris, R.W.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
30 April 1967	35	9

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
AF19(628)-3825 ARPA Order	
b. PROJECT AND TASK NO. No. 450	Final Report
8663	
c. DOD ELEMENT	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
62503015	
d. DOD SUBELEMENT	AFCRL-67-0289
N/A	

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES Prepared for	12. SPONSORING MILITARY ACTIVITY
Hq. (AFCRL (CRO)	Advanced Research Projects
United States Air Force	Agency
L.G. Hanscom Fld, Bedford, Mass 01730	

13. ABSTRACT

Techniques were developed to determine the shapes of optical objects from images corrupted by noise, diffraction and aberrations. Theoretical and experimental investigations were conducted using these techniques. The major part of the study has been reported in detail in several Scientific Reports but is reviewed here, along with the results of some preliminary and subsidiary work.

DD FORM 1473
1 JAN 64

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fourier analysis						
Diffraction						
Theoretical imaging						
Nonuniform illumination						

INSTRUCTIONS

1. **ORIGINATING ACTIVITY:** Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. **REPORT SECURITY CLASSIFICATION:** Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. **GROUP:** Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. **REPORT TITLE:** Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. **DESCRIPTIVE NOTES:** If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. **AUTHOR(S):** Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. **REPORT DATE:** Enter the date of the report as day, month, year, or month, year. If more than one date appears on the report, use date of publication.

7a. **TOTAL NUMBER OF PAGES:** The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. **NUMBER OF REFERENCES:** Enter the total number of references cited in the report.

8a. **CONTRACT OR GRANT NUMBER:** If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. **PROJECT NUMBER:** Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. **ORIGINATOR'S REPORT NUMBER(S):** Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. **OTHER REPORT NUMBER(S):** If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. **AVAILABILITY/LIMITATION NOTICES:** Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through

_____."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through

_____."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through

_____."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. **SUPPLEMENTARY NOTES:** Use for additional explanatory notes.

12. **SPONSORING MILITARY ACTIVITY:** Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. **ABSTRACT:** Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U).*

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. **KEY WORDS:** Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.